# Architecture Robustness in NASA's Moon to Mars Capability Development – FY23 Data Results

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*Abstract*— **In preparation for humanity's return to the Moon, it is important to advance technologies and capabilities that will allow for sustainability on the lunar surface and prepare for human missions to Mars. As charged in Space Policy Directive-1, NASA's Artemis program will advance and develop technologies on the lunar surface that can be leveraged towards a safe and successful human round-trip mission to Mars. NASA's Exploration Systems Development Mission Directorate Capabilities Integration Team (ESDMD CIT) is advancing a continuous effort to identify and map gaps between capabilities and anticipated human spaceflight architecture elements. As upcoming exploration missions approach, the architectural design tradespace increasingly narrows. This paper provides an updated exploration of certain architectural and element design choices for upcoming missions to the Moon and Mars, comparing and contrasting capability gaps and classes of capability gaps that are architecture robust with those that are not. In doing so, we identify certain capabilities as relevant, and therefore robust, across varying architectural possibilities while identifying other capabilities as only applicable to specific architectural pathways. Capabilities that are applicable to multiple elements across the architecture have more architectural breadth because of their increased likelihood of remaining relevant even if changes are made to some elements they are mapped to. Correspondingly, capabilities that are applicable to specific elements across the architecture but are necessary under almost any eventuality have more architectural depth because of their increased likelihood of remaining relevant even if architecture changes are made. One of the key analyses in this paper is an exploration of architecture robustness as a function of capability area, as defined by the NASA Technology Taxonomy. These results are then evaluated and analyzed across human spaceflight architecture elements to gain a greater understanding of the relationships between exploration capabilities and the systems that will eventually be implemented. Additional insights regarding investment strategies are also considered. General conclusions about these relationships are drawn.**

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## 1. Introduction

In preparation for humanity's return to the Moon, it is important to advance technologies and capabilities that will allow for sustainability on the lunar surface, as well as eventual human missions to Mars. As charged in Space Policy Directive-1 [1], NASA's Artemis program [2] will advance and develop technologies and capabilities on the lunar surface to be leveraged towards a safe and successful human round-trip mission to Mars. Across many years and successive studies, NASA has identified key aspects and investigated many architectural tradeoffs of various lunar and Mars architectures. Furthermore, NASA has invested significant efforts into developing various capabilities to support these efforts and to understand what steps must be taken now to support these upcoming missions [3]. NASA's Exploration Systems Development Mission Directorate's (ESDMD) Capabilities Integration Team (CIT) is advancing a continuous and iterative effort to identify and map gaps between exploration capabilities and anticipated human spaceflight architecture elements.

Various architecture and campaign studies were assessed, helping to determine capability needs, including the International Space Exploration Coordination Group (ISECG) Reference Architecture for Human Lunar Exploration (HLE) [4,5,6,7,8], the Mars Design Reference Architecture 5.0 (DRA 5.0) [9,10,11], and the Evolvable Mars Campaign (EMC) [12]. From these, commonalities in Moon-to-Mars needs were determined across capability areas [13]. These broad capability areas are defined in NASA's 2020 Technology Taxonomy [14] as:

1) Propulsion Systems
2) Flight Computing and Avionics
3) Power and Energy Storage
4) Robotic Systems
5) Communications, Navigation, and Orbital Debris Tracking and Characterization Systems
6) Human Health, Life Support, and Habitation Systems
7) Exploration Destination Systems
8) Sensors and Instruments
9) Entry, Descent, and Landing (EDL)
10) Autonomous Systems
11) Software, Modeling, Simulation, and Information Processing
12) Materials, Structures, Mechanical Systems, and Manufacturing

13) Ground, Test, and Surface Systems
14) Thermal Management Systems
15) Flight Vehicle Systems
16) Air Traffic Management and Range Tracking Systems
17) Guidance, Navigation, and Control

The analyses in this paper are based on data collected for NASA's 2023 ESDMD Capability Gaps Data Call, which collected information on all capability areas except 15 and 16. Furthermore, results presented here provide an update on those presented and collected for the 2019-2022 data calls [24]. The purpose of the data call was to collect and understand the gaps that exist between NASA's current capabilities and the capabilities that are required for upcoming missions across the Moon-to-Mars architecture. NASA's ESDMD CIT also describes the process for collecting and integrating the data, which can be found in [15]. As part of the subsequent analyses of the collected data, the capability gaps were mapped to applicable elements of the architecture. While key aspects of these upcoming missions are understood, other aspects are not due to architectural uncertainties in different mission segments.

## 2. Architectural Uncertainties by Segment

NASA recently released a plan for the Artemis campaign [2], and published a discussion of capability needs associated with developing a sustained presence on the Moon as well as capabilities needed for human Mars exploration that might be demonstrated using the Moon as an analogue [3]. Figure 1 provides an overview of the Artemis Campaign. This campaign can be divided into segments – Initial Human Lunar Landing, Long-Term Presence on the Lunar Surface, and Initial Human Mars Mission. Each of these segments may drive various capability needs. While many capability needs are well understood – particularly for near-term Lunar missions – there is still some uncertainty within the architectures that may impact gap assessments and therefore investment strategies.

*Initial Human Lunar Landing*

This segment requires the Orion spacecraft, the Space Launch System (SLS) rocket, and Human Landing System (HLS), which are all under development and targeting a mid-2020s lunar return. Orion is the exploration vehicle that will carry the crew to space. SLS is the rocket system currently under development to launch crew aboard Orion from Earth. HLS is the mode of transportation that will take astronauts to the lunar surface. With the elements of this segment well into development, there is little uncertainty remaining and the segment is described in some detail in the Artemis Plan [2]. The requirements and capabilities of Orion and SLS are well understood. HLS variants for the Artemis program are being developed, with at least one being selected for implementation [16]. On early missions, the astronauts will live inside the pressurized crew cabin portion of the lander for up to a week. While there are some key differences in the designs between the lander options, capability gaps that may be associated with those individual designs are outside the scope of this analysis. These systems are being developed in conjunction with the Gateway, an outpost orbiting the Moon in a Near-Rectilinear Halo Orbit (NRHO) that provides essential support for sustainable, long-term human return to the lunar surface, as well as a staging point for deep spaceexploration.

A rapid return to the Moon is facilitated by minimizing the number of systems involved with landing humans on the surface by the mid-2020s. While the Gateway will be available in its initial configuration during this segment, HLS has the option to dock with Gateway to board HLS or rendezvous directly with Orion in NRHO before two crew descend to the Lunar South Pole. For this mission, no pressurized infrastructure will have been emplaced on the surface, so the crew will live in the HLS for approximately 6.5 days and will perform up to 5 Extra Vehicular Activities (EVAs) [3].

The main area of residual uncertainty remains around the specific operations for the Artemis III mission. The precise landing site and science operations for Artemis III astronauts depends on several factors. NASA's desired traits for this landing site include i) access to significant sunlight, which provides minimal temperature variations and enables the use of solar power; ii) continuous line-of-sight to Earth for communications; iii) mild grading and surface debris for safe landing and walking or future roving mobility; and iv) close proximity to permanently shadowed regions (PSRs), some of which are believed to contain resources such as water ice. During this first week-long expedition, the crew will characterize and document the regional geology, including small PSRs, if available. The exact EVA activities will be influenced by the landing site, number of EVAs, and tools available for the crew.

*Long-Term Presence on the Lunar Surface*

After Artemis III, NASA's plans for lunar surface missions include activities to emplace the infrastructure and systems needed to enable a sustained lunar surface presence as well as activities to demonstrate the operations and extended mission durations that we will experience on human missions to Mars. The location for the infrastructure and operations is notionally called Artemis Base Camp. The specific missions and sequencing of activities to build up capabilities are still in formulation by NASA and numerous international partners that have expressed interest in lunar surface operations. International partners could provide key contributions such as rovers, surface habitats, In-Situ Resource Utilization (ISRU) related equipment, and long-duration life support systems, but key contributions including partner-provided elements have not yet been determined.

Because of this uncertainty, NASA is pursuing a communications and navigation network, known as LunaNet,

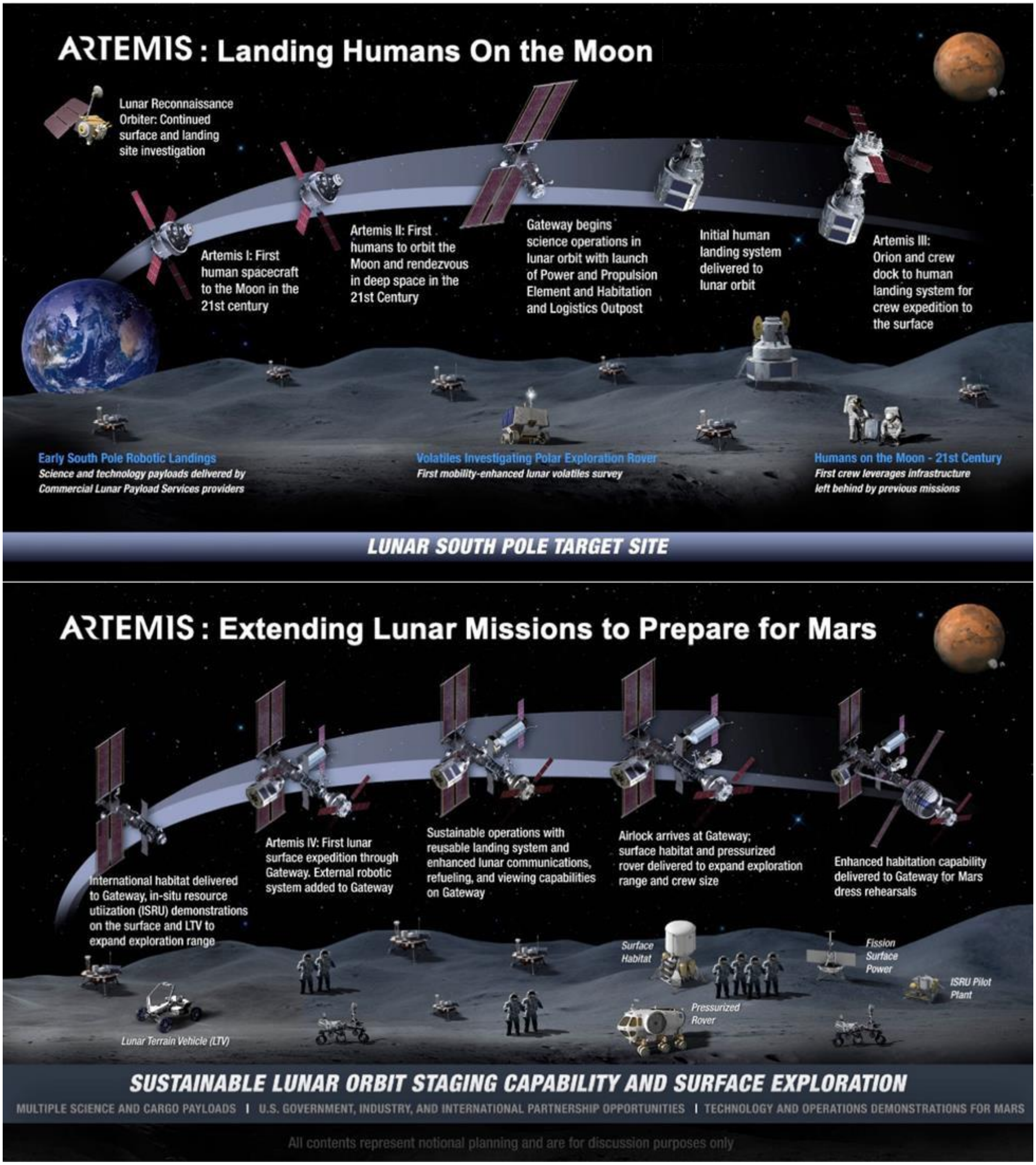


***Figure 1: Overview of NASA's Artemis Campaign***

that is extensible and flexible to enable complex lunar operations for human and robotic missions on the surface and in Cislunar space [17]. The LunaNet architecture is flexible and independent of any specific implementation concerning space platforms, frequency bands, protocols, or node providers. Implementation of LunaNet will depend upon establishing well-defined standards [18] with each node required to be interoperable with any other node and networking to allow the multi-node path between two endpoints.

The three primary mission elements of sustained lunar surface presence at Artemis Base Camp are the Lunar Terrain Vehicle (LTV), an unpressurized rover that can transport crew around the site for short distances, the Lunar Pressurized Rover, designed for long-duration trips, and the Lunar Surface Habitat (SH) as shown in Figure 2 to enable stays for four crew on the lunar surface initially for one to two months. Some key open mobility system trades include whether an airlock or suitlock will be used and whether redundant mobility systems will be required for emergency/off-nominal operations. Current plans do not include operation of crew mobility systems deep into PSRs. However, if power, thermal, and lighting systems capable of supporting such operations become available, limited PSR operations may be considered. Similar considerations are in play for robotic system operations into PSRs and deep craters that would require capability to operate on steep slopes. Specific supporting infrastructure to be added over time such as surface communications, power, radiation shielding, landing pads, and logistics are still under consideration and will evolve as specific missions are planned and as new technologies become available. Specific to power, both solar and nuclear power are in the tradespace [3]. Similarly, depending upon the ISRU pilot plant demonstration and the outcome of robotic and human missions prospecting for resources, a full-scale ISRU plant to produce water may be added and would offset other logistics requirements. Another uncertain area is the concept of operations and deployment strategy of the SH; NASA is performing studies to determine optimal strategies for this.

***Figure 2: Concept rendering of a notional lunar surface habitat.***

A core objective of the sustained lunar presence will be to conduct analog activities to understand human health impacts and develop operational approaches for future Mars exploration. Gateway's capabilities will expand throughout this segment with the addition of elements that may be provided by international partners. These elements may add capabilities such as advanced robotics, additional communications capabilities, life support systems, refueling, and logistics resupply. Included in this expansion along with those on the Mars Transit Habitat (TH) may be the evolution of Gateway's systems via addition of enhanced habitation capabilities to include larger volumes and highly reliable life support systems [19] that would be needed to support a Mars round-trip mission. Most of these capability needs are well understood and NASA has been closing capability gaps for long-duration highly reliable Environmental Control and Life Support Systems (ECLSS) utilizing the International Space Station (ISS) for many years [20]. When paired with HLS vehicles, Gateway will provide the opportunity to conduct operational analogs for Mars with long stays in orbit, at least 30 days on the surface and a subsequent stay in lunar orbit to understand the human health risks for Mars and test


***Figure 3: Lunar Missions Prepare Us for Mars***

some operations and equipment that we plan to use for Mars missions. The Mars analog missions can be lengthened with the delivery of the Transit Habitat later in this campaign segment. Minimum Mars analog mission durations needed to address human health risks are still in formulation and will be influenced by the proposed design of the first human Mars mission [25]. Much of this is summarized in Figure 3.

*Initial Human Mars Mission*

NASA's current approach for the first human Mars mission is to transport humans to Mars and back as fast and as early as possible on the TH as shown in Figure 4, with minimal infrastructure investment [3]. For this reason, NASA is currently exploring opposition class missions that take advantage of higher-energy propulsion technologies to shorten the transit, typically resulting in increased mass. However, this increase may be offset by a decrease in infrastructure and crew risk associated with a stay of only 30 days on the Martian surface rather than the 300 to 500 days typically assumed of conjunction class missions [9]. Until these trades can be balanced in terms of cost, schedule, and risk, the selection of opposition class vs. conjunction class for the first human Mars mission is an open trade that broadens the range of possible capability needs to support this mission. A specific open trade associated with Mars transit for both cargo and crew is the choice of propulsion system, with options including solar electric, nuclear thermal, and nuclear electric as well as hybrid options that would pair a traditional chemical stage with the nuclear stage or solar electric stage. For all these options, advanced cryogenic fluid management systems including zero boil-off technologies are necessary because even small amounts of boil-off over a long mission life would drive substantial propellant reserves.

***Figure 4: Concept rendering of a notional TH.***

Regardless of the mission class or any other architectural choice, EDL presents a significant challenge to achieving the goal of human exploration of the Martian surface. NASA's current approach spreads risk across multiple, smaller landers, building confidence with cargo landers ahead of the first human landing. NASA's current estimates are that three landers with 20-25 mt payload capacity will be required [3]. Robust, reliable, long-duration power systems and communications assets will be included in these pre-deployment activities. Nuclear power systems are currently the preferred option here because solar power is less reliable on Mars due to seasonable dust storms that can last for weeks or months. A range of habitation options, including both rigid and inflatable concepts are under consideration. The overall Notional Mars Mission Overview is shown in Figure 5.

A key set of open trades are under consideration in the design of the Mars Ascent Vehicle (MAV), which is returning the crew from the Martian surface after a surface stay in the Mars

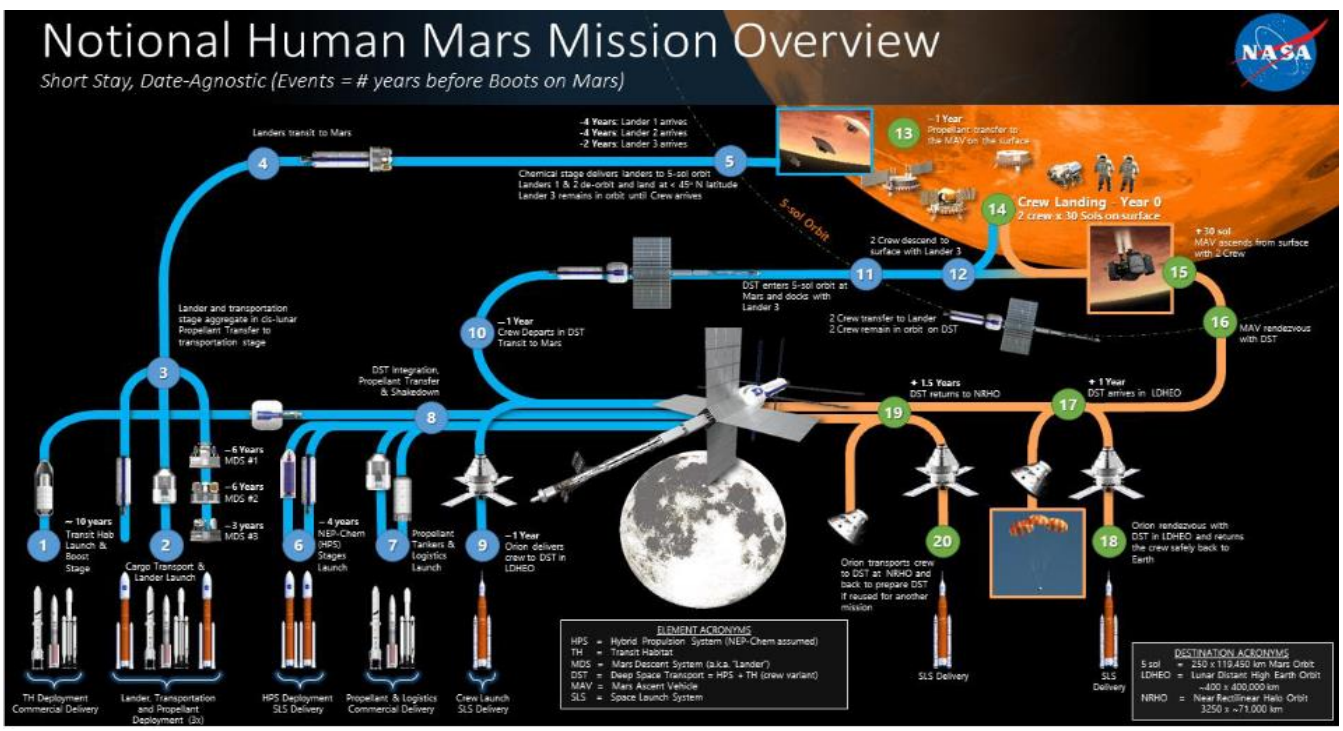


***Figure 5: Notional Human Mars Mission Overview***

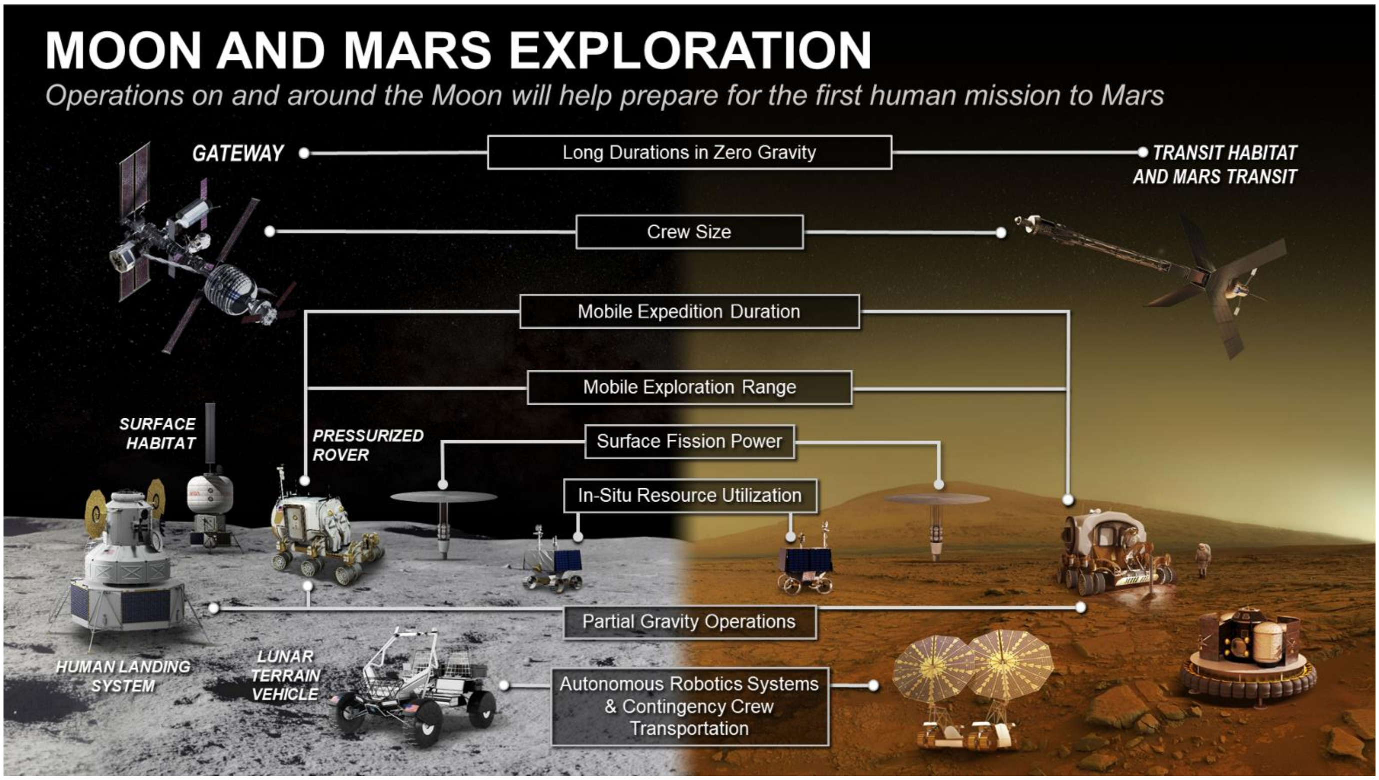


***Figure 6: Moon and Mars Exploration***

Pressurized Rover. The MAV is currently planned to be pre-deployed using one of the cargo landers mentioned above. Propellant type and fueling options are open, including landing the MAV fully or partially fueled or utilizing atmospheric ISRU to produce propellants in-situ. Figure 6 shows the overall Moon and Mars Exploration architecture common element linkages.

## 3. Architecture Robustness

There is fundamental uncertainty due to the ever-evolving architectures for Moon and Mars exploration, along with the interconnectedness of elements within these architectures. It is useful to attempt to characterize the susceptibility of capabilities to change as the architecture evolves [21]. Many capabilities are specific to a particular architectural design choice, while other capabilities are generally required regardless of architecture design specifics. The less likely a mission capability requirement is to change as the architecture evolves, the more architecture robust we define that capability to be.

There are two key ways to view architecture robustness. The first pertains to capabilities that are broadly applicable across many elements. In this case, these capabilities are robust to changes to particular elements because they are still likely to apply to unchanged elements. We define capabilities being robust to changes across element mappings as being architecturally broad. The second pertains to capabilities that are highly specific to a given element, but we know that capability need exists under any or at least many of the likely architectural scenarios. Therefore, these capabilities are robust to changes in the architecture, which we define as being architecturally deep.

Architecture breadth can be considered as a gauge for the level of need within the architecture of a given capability. As more elements are identified as requiring a given capability, the more broadly applicable that capability is. This has the potential to aid decision makers who may select a design point such as a single performance parameter for many elements for commonality or multiple design points based on element type or location. Grouping capability robustness by sets of element applicability can help to inform these decisions. On the other hand, architectural depth informs the resilience of capabilities to architectural and political changes. While it is more difficult to establish single performance parameters for architectural depth due to its higher-level architectural nature, this identifies areas that are unlikely to be changed based on changes in administration or controlling political party. It is at least in part a function of how fundamental a capability is to essential architecture elements and is generally associated with mapping to fewer elements.

Due to architectural breadth being a function of capabilities mapping to many elements and architectural depth being a function of capabilities strongly mapping to few elements, as architectural robustness increases in one direction, it tends to decrease in the other direction, although there are certainly exceptions. Based on mapping of the 2023 capability gaps to the architectural elements and averaging results for all capability areas, the relationship between architectural breadth and depth as a function of capability area is shown in Table 1.

| Architecture Robustness by Capability Area | |
|---|---|
| Capability Area | Architecture Robustness |
| 2) Flight Computing and Avionics | More Architectural Breadth |
| 11) Software, Modeling, Simulation, and Information Processing | |
| 3) Power and Energy Storage | |
| 6) Human Health, Life Support, and Habitation Systems | |
| 12) Materials and Structures | |
| 4) Robotic Systems | |
| 13) Ground, Test, and Uncrewed Surface Systems | |
| 10) Autonomous Systems | |
| 5) Communications, Navigation, and Orbital Debris Tracking and Characterization Systems | |
| 7) Exploration Destination Systems | |
| 14) Thermal Management Systems | |
| 8) Instrumentation and Sensors | |
| 9) Entry, Descent, and Landing | |
| 1) Propulsion Systems | More Architectural Depth |

**Table 1: Architecture Robustness by Capability Area**

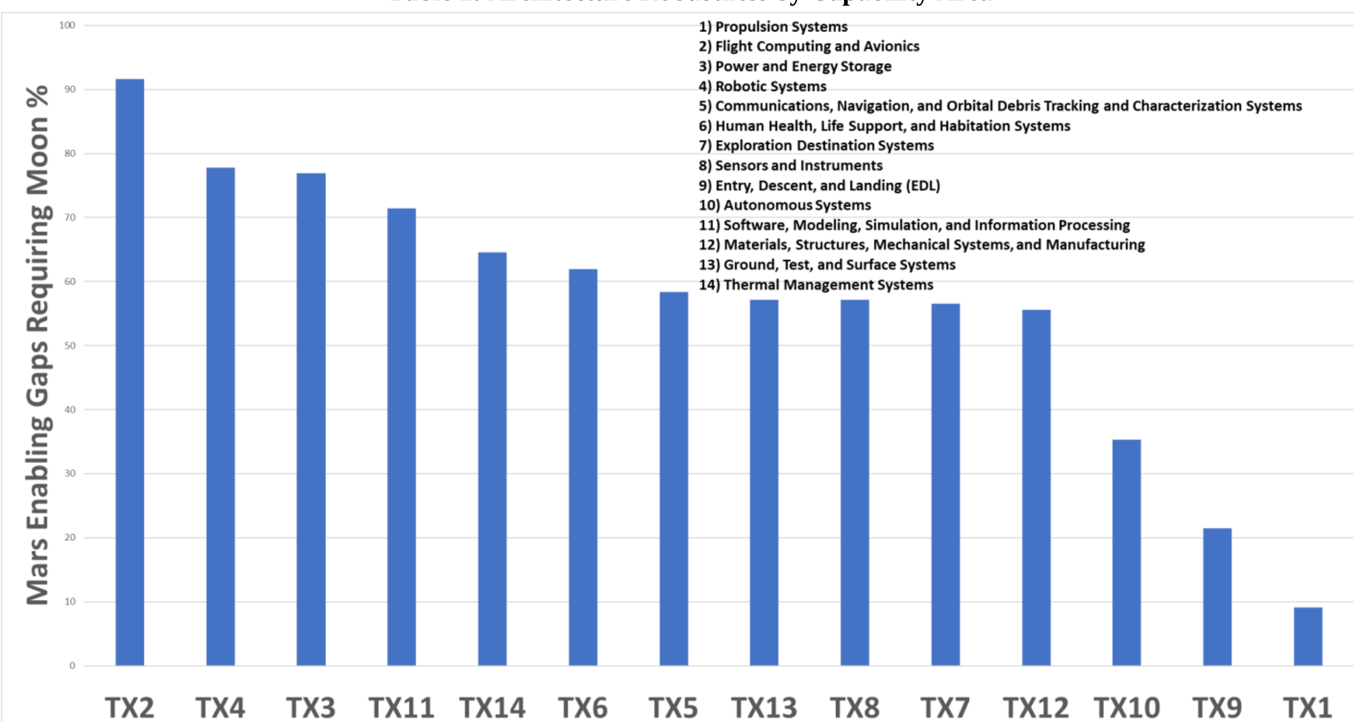


***Figure 7: % of Mars Mission Capability Gaps Dependent on Moon/Cislunar***

Given that Mars missions will require a combination of significant advancement of capabilities at the Moon and in cislunar space along with Mars-specific advancements, it can be informative to understand what percentage of capability gaps that enable Mars missions require the Moon or cislunar space to validate those capabilities. Based on the 2023 ESDMD Capability Gaps data call, Figure 7 shows what percent of Mars enabling capability gaps require the Moon or cislunar space as a prerequisite to gap closure.

Given that capability gaps that require the Moon or cislunar space to enable Mars inherently are more likely to be applicable to more architecture elements than capability gaps that do not, we infer that increasing Mars capability dependence on the Moon and cislunar is positively correlated with architectural breadth. Figure 8 shows the relationship between robustness type and Mars capability dependence on the Moon and cislunar.

We can indeed see the correlation between architectural breadth and Mars capability dependence on the Moon and cislunar space. While individual capabilities can be both architecturally broad and deep, or the reverse, we explore these tradeoffs at the higher capability area level.

capabilities that are significantly different from any lunar propulsion capabilities. Propulsion capabilities include In-Space Transportation, Descent/Ascent Systems, and Cryogenic Propellant Systems (including Cryogenic Fluid Management).

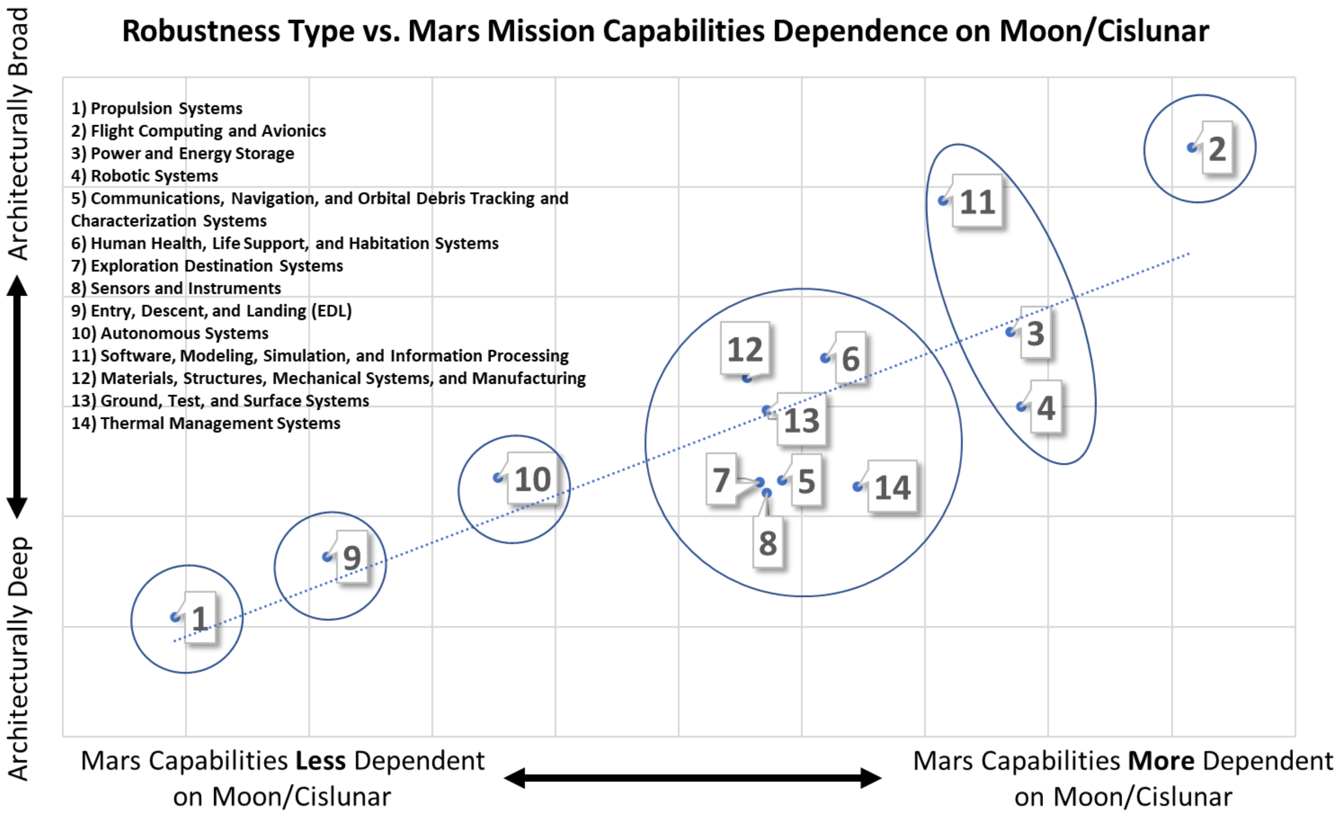


*Figure 8: Robustness and Moon to Mars*

## 4. Capabilities Discussion

The following is a discussion of capability areas clusters and their corresponding locations on Figure 8 along with highlighted capability area details and example capability gaps. As can be seen, the more dependent Mars capabilities are on the Moon/Cislunar, the more architecturally broad those capabilities tend to be. It should be noted once more that the data collected is iterative and subject to change as the architecture comes into clearer focus and as the data fidelity improves over time.

*Capability Area Clusters*

*Cluster 1: Propulsion Systems*

*1) Propulsion Systems*

As can be seen in Figure 8, Propulsion Systems are in a cluster of their own. Mars propulsion capabilities are the least dependent on the Moon and cislunar out of any capability areas. Additionally, this area is the most architecturally deep of all areas. Regardless of lunar architectural decisions, this area will still require the development of Mars propulsion

*Cluster 2: Entry, Descent, and Landing (EDL)*

*9) Entry, Descent, and Landing (EDL)*

EDL systems are highly specific to certain elements and are therefore generally architecturally deep compared with other capability areas, with Mars EDL systems capabilities generally less dependent on Moon and cislunar robotic systems capabilities than other capability areas. Regardless of lunar architectural decisions, this area will still require development of Mars EDL capabilities that are significantly different from any lunar capabilities. EDL capabilities include Aerosassist and Atmospheric Entry and Landing.

*Cluster 3: Autonomous Systems*

*10) Autonomous Systems*

Autonomous systems are also highly specific to certain elements and are therefore generally architecturally deep compared with most other capability areas, with Mars Autonomous systems capabilities generally less dependent on Moon and cislunar robotic systems capabilities than other capability areas. Regardless of lunar architectural decisions, this area will still require development of Mars Autonomous capabilities that are significantly different from any lunar capabilities. This is in part due to the increased distance of Mars from the Earth as compared with the Moon/Cislunar, which increases communication delay, decreases communication availability, and prevents rapid abort. Autonomous systems capabilities include Implementation of Autonomy, Reasoning and Acting, and Situational and Self-Awareness.

*Cluster 4: The Middle*

Most of the capability areas lie in the middle, with roughly average levels of architectural breadth/depth and average Mars capability dependence on the Moon and cislunar.

5) *Communications, Navigation, and Orbital Debris Tracking and Characterization Systems*

Communications, Navigation, and Orbital Debris Tracking and Characterization Systems capabilities include Internetworking, Position; Navigation, & Timing, and Revolutionary Communications Technologies.

6) *Human Health, Life Support, and Habitation Systems*

Human Health, Life Support, and Habitation Systems capabilities include ECLSS and Habitation Systems; Environmental Monitoring, Safety, and Emergency Response; EVA Systems; Human Health and Performance; and Radiation.

7) *Exploration Destination Systems*

Exploration Destination Systems capabilities include Dust Mitigation, Mission Operations and Safety, Planetary Protection, and Resource Utilization.

8) *Instrumentation and Sensors*

Instrumentation and Sensors capabilities include Instrumentation, Materials Characterization, Physical Sensors, and Radiation Sensing.

12) *Materials and Structures*

Materials and Structures capabilities include Structures and In-Situ Construction as well as Materials and In-Space Manufacturing (ISM).

13) *Ground, Test, and Uncrewed Surface Systems*

Ground, Test, and Uncrewed Surface Systems capabilities include Propellant Availability and Uncrewed Surface Operations.

14) *Thermal Management Systems*

Thermal Management Systems capabilities include Cryogenic Systems and Thermal Control Components and Systems.

*Cluster 5: Broad and Dependent*

The following capability areas are both architecturally broad and have Mars capabilities that are highly dependent on the Moon / Cislunar.

3) Power and Energy Storage

Power and energy storage capabilities include Power Management, Power Generation, Power Distribution, and Energy Storage.

4) Robotic Systems

Robotic systems capabilities include Rendezvous Proximity Operations and Capture (RPOC), Cargo Support, and Resource Exploration.

11) Software, Modeling, Simulation, and Information Processing

Software, Modeling, Simulation, and Information Processing capabilities include Software, Modeling / Simulation, and Security.

*Cluster 6: Flight Computing and Avionics*

2) *Flight Computing and Avionics*

Flight computing and avionics is by far the most architecturally broad of all capability areas. This is a function of the largest number of architectural elements requiring flight computing and avionics out of any capability areas. Therefore, these capabilities are the most robust to changes in element sets. Mars-related flight computing and avionics capabilities are also by far the most dependent on the Moon and cislunar capabilities of all capability areas. This indicates the essential role that the Moon and cislunar activities play in advancing these capabilities for Mars. Flight computing and avionics capabilities include Radiation- Tolerant Components and Computer-Human Interfaces (CHI).

## 5. CAMPAIGN ELEMENT CAPABILITY COMMONALITIES

We can extend the element capabilities links beyond simply Moon / Cislunar elements with Mars elements and can describe the overall amount of linkages across all architectural elements. The campaign element adjacency matrix shown in Figure 9 represents the commonality between elements as a function of shared capability gaps. The overlaps were grouped into six bins: Very High (80-100%), High (60-80%), Moderate (40-60%), Low (20-40%), Very Low (1-20%), and N/A (0%). At a high-level, this information characterizes the exploration-forward nature of each element – particularly for elements with similar functionality (e.g., habitable volumes, surface power elements, etc.). This type of information is valuable from a systems engineering and integration standpoint because it helps to identify technology development timelines (including test, demonstration, and validation needs), whether those timelines are being or should be executed in series or in parallel, and potential common standards or interface requirements in order to fully integrate the capability across the architecture. More explicitly, this matrix helps inform technology development and portfolio management by identifying focus areas to ensure that our assumptions and objectives are matching reality.

From this matrix, we can see that the most significant overlaps exist for elements with pressurized volumes (habitats and pressurized rovers). We can also corroborate heavy overlap among other architecture-dependent elements such as the Xenon Interstage and Xenon Refueling elements, the Chemical Transit Stage and the Chemical Refueling elements, and the lunar and Mars exploration extravehicular activity (xEVA) variants – more generally, space suits.

While assessing shared capability across the entire set of campaign elements is insightful for assessing broad commonalities and possible interdependencies, it is necessary to further divide the elements into groups of shared functionality. Take, for example, the previously mentioned pressurized volume elements: considering the nature of those elements is largely to support and sustain human life and human exploration, we would assume that there ought to be substantial overlap. Organizing the adjacency matrix, as in Figure 10, validates this assumption. Additionally, we confirm that sub-groupings of surface elements and pressurized rovers are being designed to ensure Mars extensibility, at least at a high level.

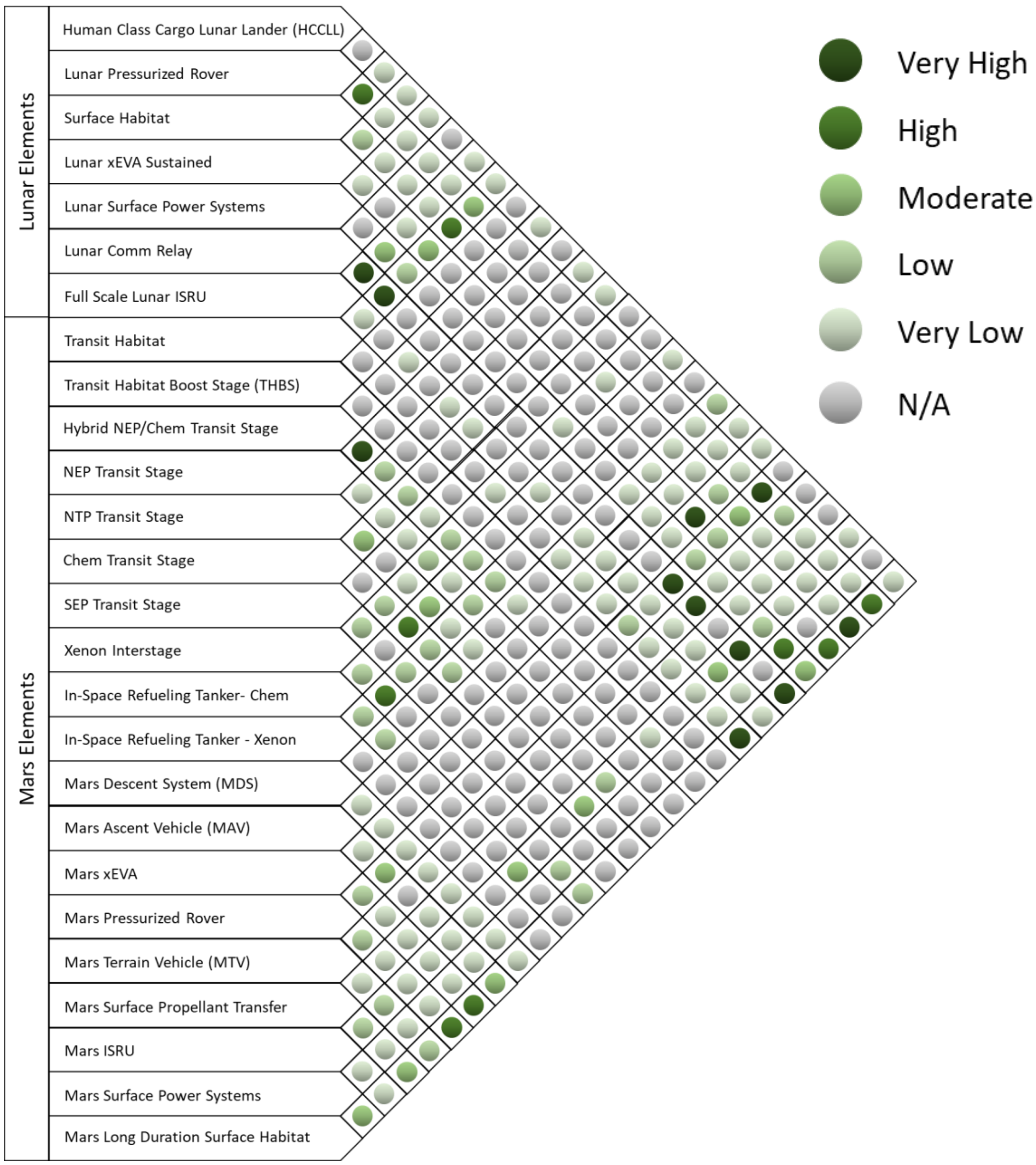


*Figure 9: Campaign Element Capabilities Overlaps*

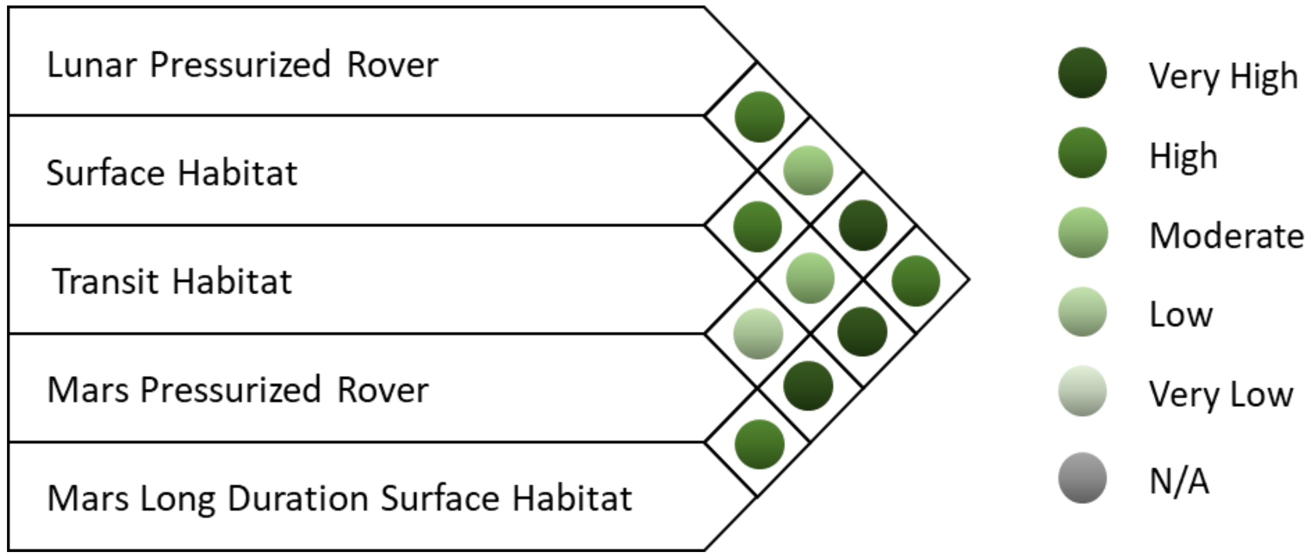


*Figure 10: Campaign Habitable Element Capabilities Overlaps*

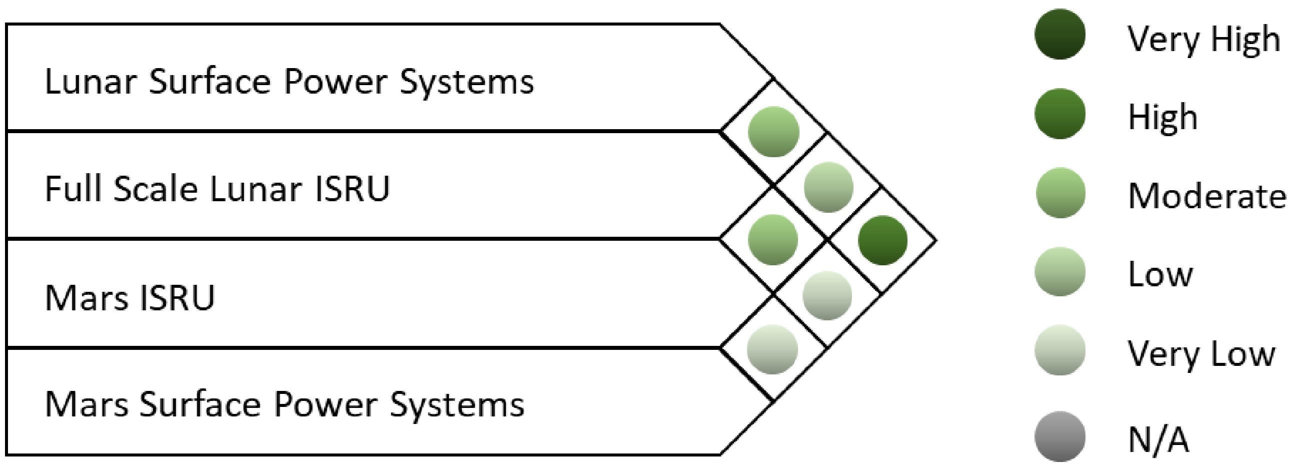


*Figure 11: Campaign Surface Power and ISRU Element Capabilities Overlaps*

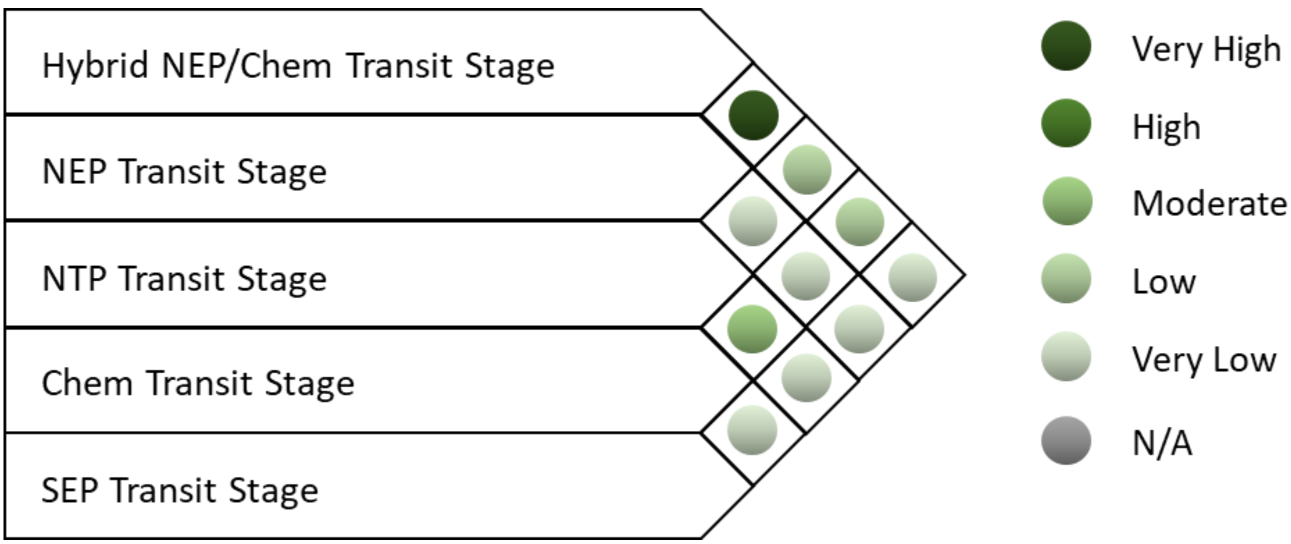


*Figure 12: Campaign Propulsion Element Capabilities Overlaps*

We can further use adjacency matrices to analyze the ordering logic of element realization throughout the campaign, as in Figure 11. Here, we see how addressing lunar surface power gaps may have risk buy-down benefits for future lunar and Mars surface systems (lunar and Mars ISRU, and Mars power systems). Assessing these capability overlaps in the context of element technology development timelines provides deep insight to potential interdependencies between elements, particularly those whose gap closure is on another element's critical path.

Across the propulsion system trade space – as in Figure 12 – we note that there is "Very Low" to "Low" overlap across dissimilar systems. As campaign analyses and systems trades are in work, we can use these overlap areas to help identify architecture-independent gaps that we can start investing in now to buy-down risk before down-selection. Some examples of these gaps include high temperature sensors for fission power systems (needed by both NEP and NTP systems), cryogenic fluid management (transfer and storage), and large-scale dynamic power conversion.

As with any higher-order analysis, it is prudent to also identify the limitations and constraints of the data being produced. The first caveat of note is that this capability identification activity is an ongoing effort that is iterated annually with the intention of capturing new or updated capability gap information as the architecture evolves. The second point is that the gaps are not all at the same level – some account for entire systems while others are decomposed to the component level. This implies some magnitude of overlap that is not accounted for in our representation. Further, many capability gaps use performance parameters that are tied to a value that is either shared by the most elements or the hardest to achieve. To that end, some of these overlaps may only represent a shared function, but the actual technological or operational implementation may be vastly different between two or more elements. Finally, it is important to note that, in some cases, the sample size is insufficient to draw meaningful conclusions; for example, the Lunar Comm Relay element only has 1 enabling gap, so any overlap with another element is listed as "Very High" (this occurred six times, in this case), or "N/A" for all others. 8 of the 26 elements represented in this analysis have less than 10 gaps associated with them. As the database continues to grow, we hope to enable deeper insights through capture of element-specific performance parameters and/or approaches based on operations, environmental conditions, gravity, etc.

## 6. CONCLUSIONS

This paper explores the tradeoffs between robustness of capability areas to certainty of architecture need and breadth of application across different elements. It also compares capability overlaps across different elements of the campaign architecture. At a high level, increase in one direction of robustness tends to lead to a decrease in the other direction. Furthermore, differences in robustness are compared across capability areas, and their correlations with overlapping Moon and Mars capabilities are explored. Understanding of these tradeoffs and impacts of prioritizing architectural breadth vs. depth can inform agency strategic planning and investment strategies regarding capability selection and investment timing. Further analysis is required to determine tradeoffs at lower system-level capabilities between architectural breadth and depth. It is certainly possible that individual component-level capabilities can have high levels of both architectural breadth and depth if that capability is certain to be required across many elements. The reverse is also possible. As the ESDMD Capability Integration efforts mature, updating this analysis will likely yield more accurate results as data improves in quality and architecture elements and functions are further defined. Furthermore, future work in this area can provide support to additional data to inform NASA investment decision cycles.

## ACKNOWLEDGEMENTS

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